Abstract—With the near extinction of many spawning aggregations of large grouper and snapper throughout the Caribbean, Gulf, and tropical Atlantic, we need to provide baselines for their conservation. Thus, there is a critical need to develop techniques rapidly assessing the remaining known (and unknown) aggregations. To this end we used mobile hydroacoustic surveys to estimate the density, spatial extent, and total abundance of a Nassau grouper spawning aggregation at Little Cayman Island, Cayman Islands, BWI. Hydroacoustic estimates of abundance, density, and spatial extent were similar on two sampling occasions. The location and approximate spatial extent of the Nassau grouper spawning aggregation near the shelf-break was corroborated by diver visual observations. Hydroacoustic density estimates were, overall, three-times higher than the average density observed by divers; however, we note that in some instances diver-estimated densities in localized areas were similar to hydroacoustic density estimates. The resolution of the hydroacoustic transects and geostatistical interpolation may have resulted in over-estimates in fish abundance, but still provided reasonable estimates of total spatial extent of the aggregation. Limitations in bottom time for scuba and visibility resulted in poor coverage of the entire Nassau grouper aggregation and low estimates of abundance when compared to hydroacoustic estimates. Although the majority of fish in the aggregation were well off bottom, fish that were sometimes in close proximity to the seafloor were not detected by the hydroacoustic survey. We conclude that diver observations of fish spawning aggregations are critical to interpretations of hydroacoustic surveys, and that hydroacoustic surveys provide a more accurate estimate of overall fish abundance and spatial extent than diver observations. Thus, hydroacoustics is an emerging technology that, when coupled with diver observations, provides a comprehensive survey method for monitoring spawning aggregations of fish.

Nassau grouper (*Epinephelus striatus*) spawning aggregations: hydroacoustic surveys and geostatistical analysis

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Introduction

Reef fish spawning aggregations have gained distinction in terms of their importance in species conservation and their socio-economic contribution to many Caribbean, tropical western Atlantic, and Gulf of Mexico fishing communities. With the near extinction of many spawning aggregations of large grouper and snapper throughout the Caribbean, Gulf, and tropical western Atlantic, it is essential that we increase our ability to study and document the remaining known (and unknown) aggregations to provide baselines for their conservation (Sadovy, 1994; Sadovy, 1997; Sala et al., 2001; Colin et al., 2003).

The Nassau grouper (*Epinephelus striatus*) is a commercially important tropical reef species that forms discrete spawning aggregations, typically around full moons from December to March (Sadovy and Eklund, 1999). Historically, spawning aggregations of Nassau grouper have occurred throughout the Caribbean, tropical western Atlantic, and Bermuda (Sadovy, 1997; Sadovy and Eklund, 1999). Nassau grouper often migrate great distances (in some cases documented on a scale of 100's of km) to aggregate on reefs at promontories of islands (Colin et al., 1987; Colin, 1992; Bolden, 2000). Long-term monitoring and anecdotal evidence from fisheries have documented use of the same site by some aggregations for as long as 30 years, suggesting high site fidelity by the species (Colin, 1996). Nassau grouper have been the most valuable finfish in the insular Caribbean and the tropical western Atlantic (Sadovy and Eklund, 1999; Sala et al., 2001), and heavy exploitation primarily during spawning seasons has resulted in local extirpation of most aggregations in the Cayman Islands, Bahamas, and Belize (Sadovy, 1997; Sala et al., 2001).

Hydroacoustics has emerged as a valuable tool in fishery population assessments throughout the world. Hydroacoustics provides a method of 1) non-invasively sampling fish

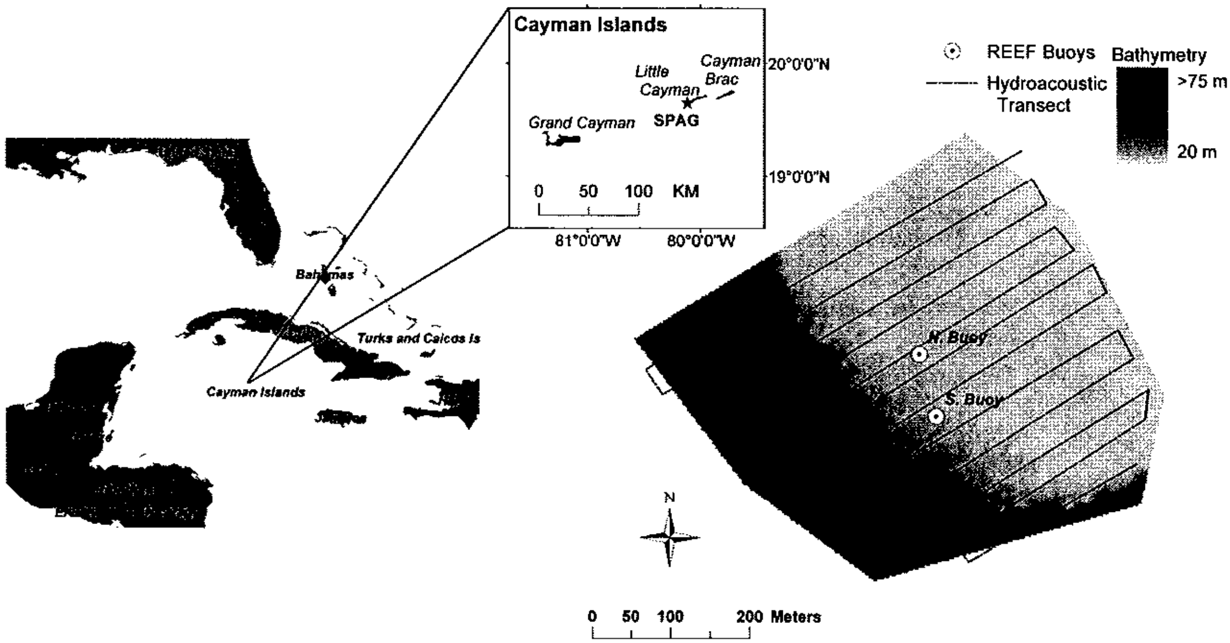

Figure 1

Nassau grouper spawning aggregation survey site at Little Cayman Island, Cayman Islands, BWI, as indicated by star and spawning aggregation (SPAG) in inset. Reef Environmental Education Foundation (REEF) marker buoys (north and south buoys) indicate location of 100-m dive transect line parallel to shelf-break. Idealized rectangular hydroacoustic transect design is overlaid on interpolated bathymetry, which is represented as grayscale shading. The hydroacoustics transect was completely surveyed twice in two segments.

communities, 2) collecting spatially continuous data in three dimensions along transects providing distribution information on sub-meter to kilometer scales, and 3) rapidly assessing fish abundance and distribution over large areas within marine systems. While the technology provides acoustic size of fish targets, supplemental sampling or groundtruthing is still needed to identify species composition and verify size distributions.

Applying fisheries hydroacoustics to assess reef species is rarely done, because it is difficult to verify species and resolve fish targets closely associated with bottom relief. Hydroacoustics may be useful in situations where fish form very large, single species aggregations during spawning, as observed in cod (*Gadus morhua*) (Lawson and Rose, 2000) and orange roughy (*Hoplostethus atlanticus*) (Bull et al., 2001). Formation of very large aggregations (>1000 fish) makes underwater visual censuses by scuba divers and assessments of spatial distributions difficult due to limitations in bottom time (especially at depths exceeding 30 m) and visibility (often reduced due to low water clarity and low light conditions). In such cases, hydroacoustics may provide a suitable means to assess reef fish abundance.

The objectives of this work were to 1) test the applicability of mobile hydroacoustics as a repeatable survey method to rapidly assess a Nassau grouper spawning aggregation, 2) apply geostatistical models to produce objective measures of the spatial extent and total abundance of grouper in an aggregation, and 3) compare distribution, density, and abundance estimates with diver-visual surveys. For this paper, we focus on a survey of a single Nassau grouper spawning aggregation at Little Cayman Island, Cayman Islands, BWI, in January 2003.

Methods

Study sites

Hydroacoustic and diver surveys were conducted near Little Cayman Island, Cayman Islands, BWI, on 23 January 2003 (Fig. 1). The site is located on a promontory on the southwestern end of Little Cayman. The shelf slopes from shore out 0.6 km to a depth of 24–33 m at the shelf edge (Fig. 1). Bottom relief at the site is as much as 5 m and made up of hard and soft corals, sponges, and large expanses of sand. Scientists have observed annual spawning aggregations of Nassau grouper at this site since 2001 (Whaylen et al., 2004).

Underwater visual survey

Scuba divers conducted underwater visual surveys beginning at 1430h on 23 January 2003. Marker buoys were deployed by Reef Environmental Education Foundation (REEF) at the end of a 100-m transect line. The transect line ran parallel to the shelf-break and served as a general marker for the location of the aggregation. It was located approximately 20 m inshore of the main group of aggregating Nassau grouper (Fig. 1). Three divers spent approximately 35 to 50 minutes in the water and either swam on the shoreward side of the 100 m transect line, swam as far as 100 m to the southeast of the line, or maintained position at a point along the transect and documented fish behaviors, color patterns, and estimated total abundance. Divers estimated their area searched using the 100-m transect line as a reference. Divers also used 30-cm measuring poles to estimate fish lengths underwater. The total number of fish at the aggregation site was subsequently estimated by at least one of the divers. Density estimates were calculated by dividing the total counts made by divers by the estimated area searched.

Hydroacoustic equipment deployment

The hydroacoustic survey was conducted during the afternoon immediately following the dive survey. The hydroacoustic survey design consisted of a set of 9 to 16 parallel transects 0.3 to 0.5 km in length and spaced approximately 20- to 30-m apart. Transects ran perpendicular to shore from the 20-m depth contour nearshore to >100-m depths offshore (Fig. 1). The complete set of transects was covered twice in two survey segments. The first segment began at 1550 h, and the second segment began at 1640 h.

We used a HTI Model 241 200 kHz split-beam echosounder (Hydroacoustic Technology Incorporated, Seattle, WA) coupled with a circular (6° nominal beam dimension) transducer. The transducer was mounted to a 1.2-m long towbody towed 0.5- 1.5-m below the water surface rigged from a 1.5-m boom attached mid-ship on the starboard side of a 9-m dive support vessel traveling at about 2 m s^{-1}. Rigging of the towbody included a shock-dampening system that minimized the oscillations due to pitch and roll of the vessel. Ping rate was 5 pulses s^{-1} and the pulse width was 0.18 ms during all transect runs. Target resolution was calculated based on pulse width and sound velocity and found to be approximately 0.2 m; however due to significant bottom relief, fish targets were usually not resolved from reefs at distances less than about 1 m. At the beginning of the cruise we conducted an *in situ* system calibration using a tungsten-carbide reference sphere of known target strength placed greater than 5-m from the transducer (MacLennan and Simmonds, 1992). The data were acquired in real-time for split-beam and echo-integration data processing (HTI DEP v. 3.54, HTI Seattle, WA) and stored as text files on a laptop computer for data analyses.

Hydroacoustic data processing

Hydroacoustic data were post-processed using split-beam and echo-integration analyses. Split-beam analysis was used to determine acoustic size (target strength) of individual fish targets in decibels (dB). Algorithms were used to accumulate several consecutive echoes from individual fish to produce an average acoustic size and 3-dimensional position within the water column (HTI Echoscape v. 2.11, HTI, Seattle, WA). Target strength is proportional to fish size (MacLennan and Simmonds, 1992), and using established equations for reef species encountered during previous studies (Ehrhardt and Deleveaux[1]), target strengths were converted to fish size (cm TL) and verified to species during dive surveys. Only fish target strengths between –50 and –25 dB were used for split-beam analysis, representing the range of fish sizes observed by divers. Split-beam analysis was used to locate and enumerate large targets that likely represented Nassau grouper. On numerous occasions during the surveys of the aggregation site at Little Cayman, fish targets were densely packed, making split-beam analysis difficult due to overlapping echoes. In these instances, individual targets that were on the periphery of the aggregation were used to generate size estimates.

When targets overlapped and individual echoes were not discernable, echo-integration was used to estimate density of fishes present. Echo-integration (EI) is based on the principle that the total sound energy returned from an ensonified volume of water is proportional to the fish density. When scaled to the average fish size observed, volumetric densities (fish m^{-3}) can be estimated. Returning acoustic energy was binned into georeferenced (latitude/longitude) elementary distance sampling units (EDSU) having dimensions of 20-m along the horizontal axis and 0.25-m on the vertical axis. For each EDSU, the average fish size was determined through split-beam analysis, either from analyses of fish in that cell or mean size of the fish observed along the transect when single targets were not discernable within

[1] Ehrhardt, N. M., and V. Deleveaux. 1999. Report on the 1999 Nassau grouper stock assessment in the Bahamas. University of Miami RSMAS/MBF, Miami, FL 33149-1098.

a cell. The total acoustic energy was then standardized by this average fish acoustic size, which allowed for estimates of absolute fish density (fish m^{-3}) for each EDSU. Two-dimensional densities (fish m^{-2}) were then calculated by summing the density estimates for each EDSU in the vertical dimension.

Abundance estimates

Mean fish density, spatial extent, and total fish abundance were calculated for each of the two survey segments. An estimate of total survey coverage was also calculated using the georeferenced transects in a GIS. Total abundance was calculated using arithmetic extrapolation and geostatistical modeling. First, mean fish density, calculated from all EDSUs in the entire sampling region, was extrapolated over the total survey area. Second, we used a two-stage geostatistical modeling procedure to estimate the spatial extent, fish density, and total fish abundance within the aggregation. Echo integration data from each transect was reclassified as a "mark" and scored as a one when fish were present within an EDSU; when they were absent, they were not a "mark" and scored as a zero. The spatial structure of the "marks" was calculated using a classical variogram estimator and a spherical variogram model was fitted with weighted non-linear least squares (Cressie, 1993). The survey area was divided into 20-m square cells and indicator kriging was used to predict the probability of a "mark" occurring in each of the cells based on the variogram and proximity to the sampled locations (Rossi et al., 1992). Cells for which the probability of occurrence was greater than 0.5 were designated as "mark." The number of marked cells and total area were calculated to determine the spatial extent (in m^2) of the aggregation during each segment. The second stage of the modeling procedure used block kriging to determine the average density within the predicted "mark" region (Isaaks and Srivastava, 1989; Cressie, 1993). Block-kriged mean fish density was extrapolated over the estimated spatial extent of the aggregation to produce a global estimate of fish abundance for each sampling segment. All spatial analyses and visualizations were performed in SPLUS (v. 6.1, Insightful Corp., Seattle, WA) and ARCVIEW (v. 8.3, ESRI Corp., Redlands, CA).

Results

Dive survey

Divers counted a total of 450 grouper over approximately 5,400 m^2 searched. Fish were observed in three separate groups, one group south of the south buoy of the 100-m transect (250 fish in approximately 900 m^2), another group on the southern end of the 100-m dive transect (150 fish in approximately 2000 m^2), and a smaller group of fish lying on the bottom to the northeast and closer to shore (50 fish in approximately 2500 m^2). Observations from divers identified and visually estimated lengths of 20 Nassau grouper with an average of 60 cm TL and a range of 35 to 75 cm TL.

Hydroacoustic survey

Dense aggregations of Nassau grouper were observed during both segments of the hydroacoustic survey resulting in occasions where individual echoes were not discernable due to fish target overlap. Statistics on target strengths were limited to tracks that had a minimum of four echoes in a sequence and produced traces indicative of a single fish passing through the acoustic beam. Typically, these targets were located on the outer boundaries (either vertically or horizontally) of the aggregation. Individual fish sizes ranged from –26 – –46 dB. Using established conversion equations, these target sizes equate to Nassau grouper of approximately 60–90 cm TL. There was no significant difference between fish sizes observed during the two segments (Kolmogorov-Smirnov test, $P>0.1$), though the number of targets differed between segments. A total of 135 and 90 targets were tracked during the first and second segment, respectively.

The location of the aggregation was restricted to the shelf break on the southern portion of the survey region (Fig. 2). In most cases, the Nassau grouper aggregation was well off the bottom (Fig. 3). Other aggregations of relatively large acoustic targets were observed outside the region typically observed by divers. Because we could not be sure that these targets were Nassau grouper, those marks were not included in estimates of aggregation spatial extent or fish abundance. Fish density estimates for the two segments ranged from 0 to 1.50 fish m^{-2} (0 to 1.05 fish m^{-3}) and 0 to 1.05 fish m^{-2} (0 to 0.74 fish^{-3}), respectively. Average estimated fish density over the entire survey region, ignoring spatial correlation in the data, was 0.05 and 0.03 fish m^{-2} for segment 1 and 2, respectively. Total spatial coverage of the survey was approximately 134,266 m^2. Extrapolating these average fish density estimates over the entire sampling region resulted in total fish abundances of 6713 and 4027 fish in segment 1 and 2, respectively.

Both segments produced similar spatial extent maps with fish located from just south of the north buoy to nearly 200 m south of the south buoy (Fig. 2). Estimated spatial extents for the aggregation during the two segments were 6372 m^2 and 9628 m^2, respectively. Average density within the aggregation was 0.32 and 0.21 fish m^{-2} for segments 1 and 2, respectively. Abundance estimates

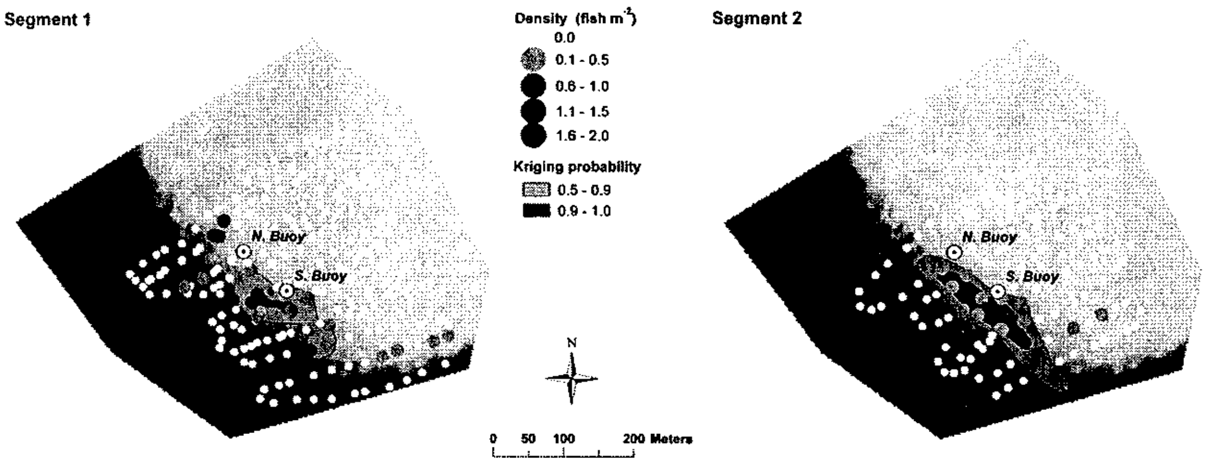

Figure 2

Distribution of Nassau grouper densities from two segments of the hydroacoustic survey of the Little Cayman spawning aggregation site. Bathymetry and REEF marker buoys are shown as in Fig. 1. White circles indicate zero fish observed, positive densities are according to gray scale in legend. Results of indicator kriging of spatial extent of the fish aggregation are noted by outlined grayscale-shaded polygons indicating probability of occurrence.

using the two-stage kriging procedure were 2039 fish for segment 1 and 2022 fish for segment 2.

Discussion

We successfully located the Nassau grouper spawning aggregation off Little Cayman, BWI during both segments of the hydroacoustic survey. In general, the aggregation was observed at or near the shelf-break, although divers observed a smaller group of fish shoreward of the shelf-break that was not observed during the hydroacoustic survey. This may be because the acoustic transects did not cover this area adequately, the fish were too close to the bottom to be detected, or the grouper had moved prior to the hydroacoustic transect coverage. In some cases, other groups of large acoustic targets were located well outside the region observed by the divers. Because previous surveys of Nassau grouper showed that in certain instances target strengths of other species were sometimes quite similar to Nassau grouper, we were reluctant to assign these targets to the Nassau grouper abundance estimate (Taylor, Eggleston, and Rand, unpubl. data). Unfortunately, it was not feasible to use divers to verify the species in these outer groups, so their identity remains unknown. Estimates of the spatial extent and abundance were restricted to those regions that were surveyed by divers.

Other species are known to use the site at Little Cayman as a spawning aggregation site (Whaylen et al., 2004). During our study, the Little Cayman aggregation site did contain a mix of smaller species in close proximity to the Nassau grouper. When smaller fish were mixed in with the Nassau grouper, it was easy to delineate larger targets that were likely grouper from the smaller targets that represented other smaller species. Larger species such as bar jack (*Caranz rubber*) and horse-eye jack (*Caranx latus*) were also present at the aggregation site during our study, but these species were located over deeper water or were distant from the main concentration of Nassau grouper. These marks were excluded from the acoustic analysis.

Average density of Nassau grouper over the entire survey region estimated arithmetically from hydroacoustic data was similar to the average overall grouper density estimated from the dive survey. Grouper densities within the aggregation site estimated using hydroacoustics were on average three times the average density observed by divers; however, densities as high as 0.27 fish m^{-2} were observed by divers in one of the three separate groups. During this survey, it was clear that fish density was not uniform over the aggregation site. Other observations using underwater video provide indications that volumetric densities varied throughout the aggregation and were even twice as high as those observed using hydroacoustics (Rand, unpubl. data). These high fish densities were restricted to a very localized region within the aggregation site and may have been missed by the hydroacoustics or difficult to quantify by divers. Patchy or non-uniform distributions of fishes at spawn-

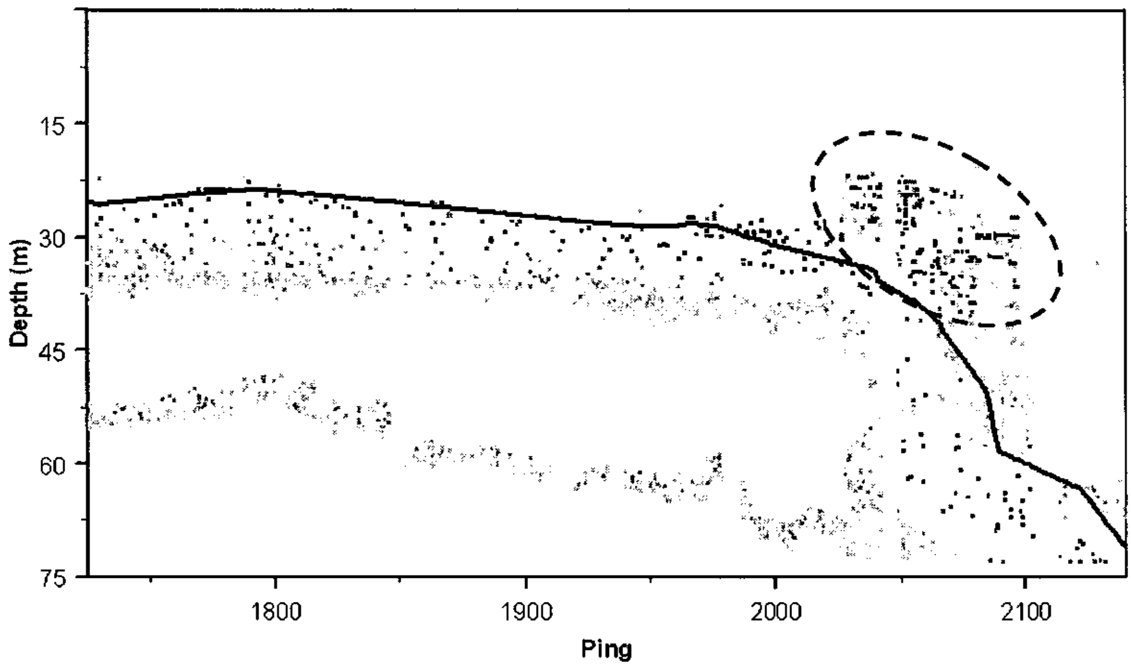

Figure 3

Echogram example for a Nassau grouper spawning aggregation positioned at the shelf break at the Little Cayman site highlighted by hashed oval. Fifty pings along the x-axis represent approximately 20 m linear distance.

ing aggregation sites has been observed in other reef fish species (Shapiro et al., 1993).

Although estimates of average grouper densities over the entire region were similar between divers and hydroacoustics, total abundance estimates were not. The large differences in areas searched by each method may help to explain the discrepancies between the total abundance estimates from the two methods. The divers were only able to survey a total of 5400 m^2 compared to over 134,000 m^2 surveyed using hydroacoustics. Diver observations also may have been confounded by low water clarity and light level, which limits visibility, especially during dusk. In some cases, especially during periods of high grouper densities, it may have been difficult for divers to make accurate counts of fish that were exhibiting rapid movements. Due to limitations in bottom time using scuba, divers were not able to search the entire areal extent of the grouper aggregations as revealed by the hydroacoustics.

The extrapolation of the arithmetic hydroacoustic density estimates over the entire survey region produced abundance estimates that were two to three times higher than the estimates using the geostatistical models. The arithmetic estimates were also an order of magnitude higher than those made by divers. This result comes as no surprise as the presence of spatial correlation in the data, particularly the patchy nature of spawning aggregations, can result in significant biases in global estimates of abundance. Previous efforts to estimate Nassau grouper population abundance using a simple extrapolation method have been criticized for not recognizing such biases (Ehrhardt and Deleveaux[1]; Gascoigne[2]). Abundance estimates calculated using the two-stage kriging method, on the other hand, implicitly incorporate the patchy nature of the distribution pattern and produce a more robust estimate of abundance. Still, there may be some limitations to this two-stage kriging approach. First, abundance estimates using this method are dependent upon accurate estimates of the spatial extent of the aggregation. The hydroacoustic transects were spaced 30 m apart and kriging probability interpolations may have interpolated high densities of fishes between transects, when in fact the groups may have been separated by as much as 30 m. This was likely the case for our estimates of grouper abundance and spatial extent on the mid-day survey of 23 January 2003, since divers reported a disaggregated pattern of distri-

[2] Gascoigne, J. 2002. Nassau grouper and queen conch in the Bahamas: State and management options. 44+iv p. [vailable at http://www.breef.org/groupersummary.pdf [Accessed 20 December 2004.]

bution. A closer examination of the density distributions during segment 1 indicates a possible break in the high-density marks, implying that the Nassau grouper were in separate groups. The region of this separation was not sampled during segment 2 (Fig. 2).

Previous applications of hydroacoustics coupled with geostatistical approaches have worked well on other aggregating species (Rivoirard et al., 2000). For deep-water species such as cod (*Gadus morhua*) and orange roughy (*Hoplostethus atlanticus*), acoustics provide the principal method for fishery independent population estimates during spawning periods (Lawson and Rose, 2000; Bull et al., 2001). The orange roughy typically forms a contiguous group over deep sea mounts (Doonan et al., 2003). Using a star-transect pattern and analyzing the data using a similar two-stage kriging model, Doonan et al. (2003) estimated orange roughy abundance with good precision. However, they do note that accurately positioning the aggregation in the transect pattern can affect the precision of the spatial extent and abundance estimates (Doonan et al., 2003). If fish are not in a contiguous unit, as was the case in our study, abundance estimates may not be as reliable (Doonan et al., 2003).

Despite difficulties making accurate estimates of abundance under patchy fish distributions, mobile hydroacoustic surveys coupled with the geostatistical probability mapping still provides an objective, repeatable measure of the spatial extent of the aggregation. Estimates such as these are valuable when establishing boundaries for reserves or area closures during spawning seasons, and in estimating overall fish abundance (Glazer and Delgado, this issue).

A recognized limitation of the acoustic method is that the fish need to be greater than 1–2 m from the bottom relief to be detected. Large reef species such as snapper and grouper are known to be cryptic and closely associated with the structure of the bottom (Sale and Douglas, 1981). Previous efforts to survey hard-bottom habitats have documented difficulties in detecting fish targets when they are in close proximity (<1-m) to the bottom (Gledhill et al., 1996). Diver observations during our afternoon survey of the Nassau grouper spawning aggregation at Little Cayman found numerous fish on or very close to the bottom. Observations made by divers during surveys of this Nassau grouper spawning aggregation at others times of the day found that most fish were well off bottom during dusk and evening surveys, presumably when fish were exhibiting more spawning behavior. When abundance estimates are desired for Nassau grouper, hydroacoustic surveys may be best suited for dusk or night periods when the fish are well into the water column (Whaylen et al., 2004). In addition to verifying species, observations by divers can provide critical data on the diel behaviors of the species and provide valuable insight into the best approach for conducting mobile hydroacoustic surveys of a known spawning aggregation.

Conclusions

The mobile hydroacoustic method provided a valuable sampling method for surveying Nassau grouper spawning aggregations. Our technique provided a means to rapidly cover large (>100,000 m^2 in less than 1 h) areas when compared to underwater visual surveys using divers (<5500 m^2 in 0.5 h). Analyzing the data using the geostatistical probability mapping provided an objective measure of the spatial extent of the aggregation. In our study, the presence and location of the Nassau grouper aggregation at Little Cayman was well-known. In many cases, however, the location of an aggregation is unknown, or may have moved several hundreds of meters on a promontory (Colin, 1992; Sala et al., 2001). In these cases, hydroacoustics can provide a method to initially survey a relatively large area and locate large targets before using divers for more fine-scale observations of fish distribution and abundance patterns, and species identification. Alternatively, coarse transects could be used to locate patches or aggregations of grouper followed by a finer-scale transect design to characterize the smaller-scale spatial structure of the group. This adaptive sampling approach can have significant advantages over a simple random stratified approach for rare, patchy or aggregating populations (Everson et al., 1996; Hanselman et al., 2003). Other advances in technology such as remotely operated vehicles (Adams et al., 1995; Johnson et al., 2003) may provide additional means to identify large targets prior to using divers to make visual observations. Thus, hydroacoustics is an emerging technology that, when coupled with diver observations, provides a comprehensive survey method for monitoring spawning aggregations of reef fishes.

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